# Investigating the climate sensitivity differences between CESM1 and CESM2 in 4x$CO_2$ runs and SOM runs.

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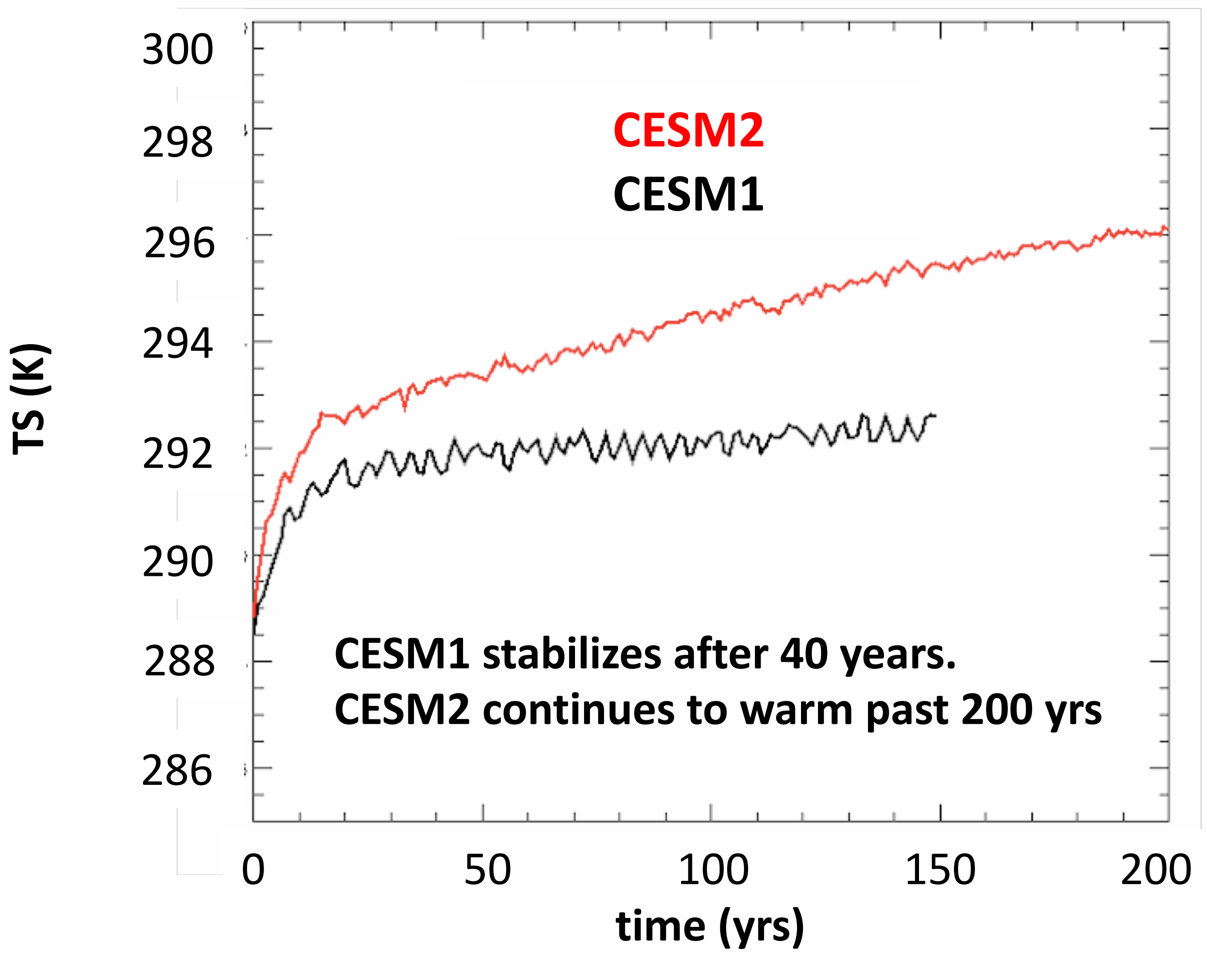
# Motivation

Abrupt 4xCO2 runs => behavior is different in CESM1 and CESM2

Increase in global TS after abrupt 4XCO2



# Motivation

- **Equilibrium Climate Sensitivity (ECS) is larger in CESM2 than in previous versions of the model.**

Equilibrium Climate Sensitivity

| | |
|---|---|
| CCSM3 (CAM3) | 2.9 K |
| CCSM4 (CAM4) | 3.2 K |
| CESM1 (CAM5) | 4.1 K |
| CESM2 (CAM6) | 5.3 K |

***IPCC (AR5): ECS is likely between 1.5°C and 4.5°C***

- **Why is ECS larger ?**

# Outline

- **Motivation**
- **Climate sensitivity in a nutshell**
- **4xCO2 fully coupled experiments**
- **Slab Ocean Model (SOM) experiments**
- **Conclusions and what's next ?**

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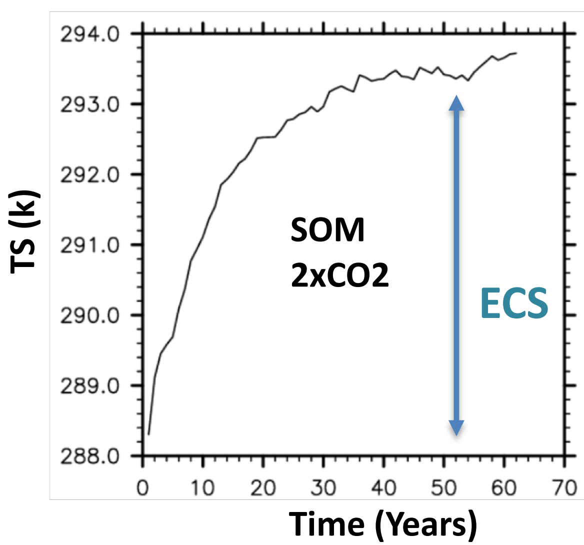
# Climate sensitivity: Cheat-sheet

**Climate sensitivity** = **Equilibrium temperature change in response to abrupt 2 x $CO_2$.**

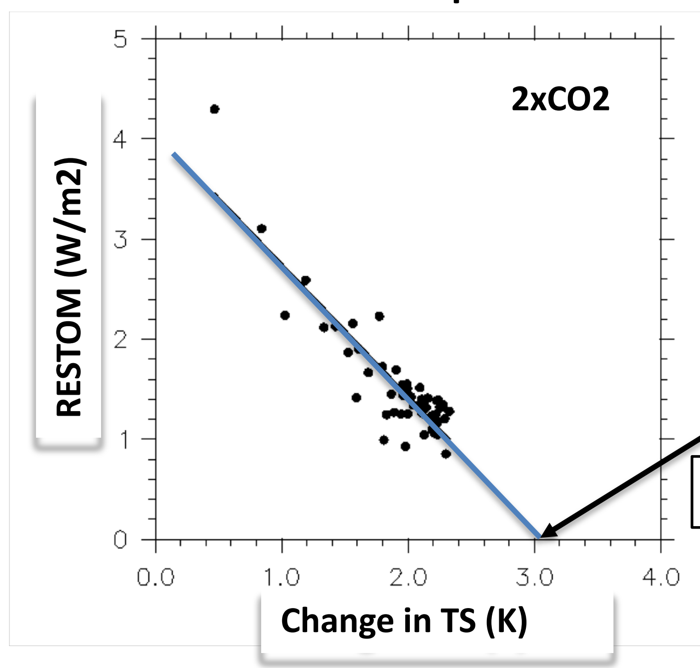
## Run to a steady state

- SOM run ($60^{+}$ yrs)
- Fully coupled run (1000 yrs?)




## Gregory method (2004)

- SOM run or coupled run




X-Intercept: ECS

$\Delta TS = ECS + a*RESTOM$

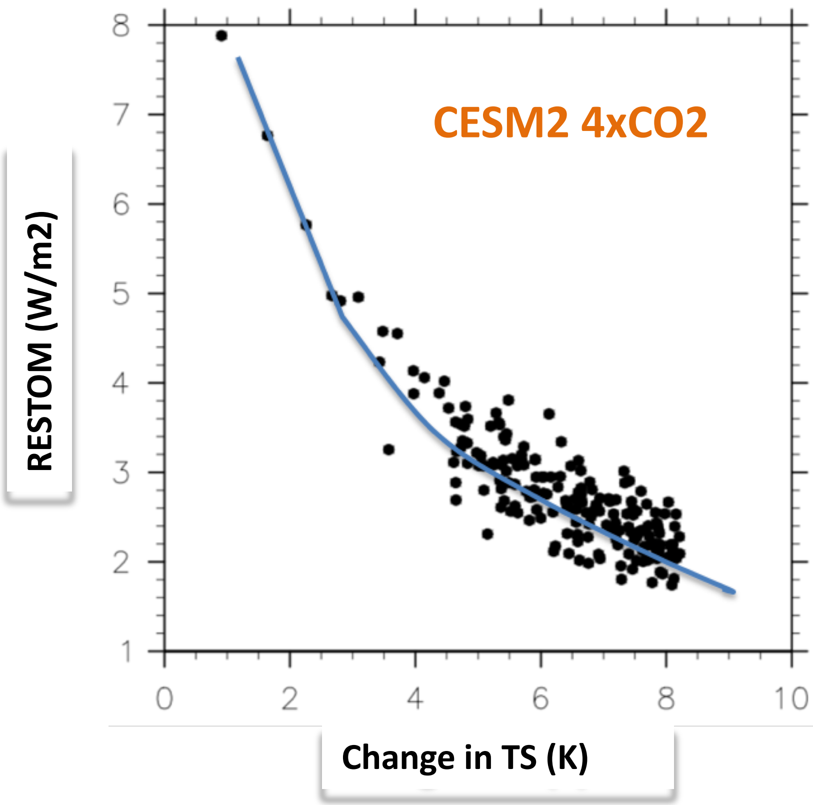
**Advantage:** Doesn't need to reach a steady state

**Caveat:** Use linear fit between RESTOM and $\Delta T$

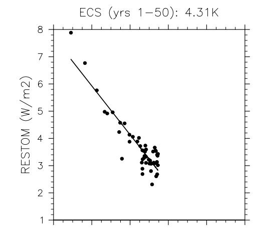
## + Other methods

# Gregory method's caveat for coupled run

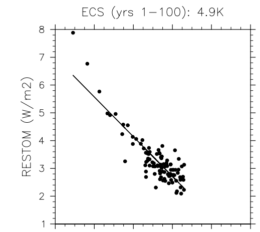
**Gregory method: Use linear fit between RESTOM and ΔT**



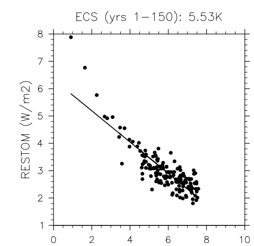

**Yrs 1-50**
**ECS = 4.31 K**



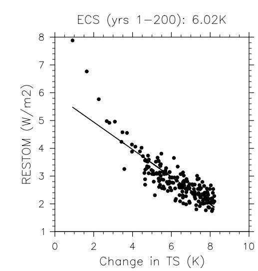

**Yrs 1-100**
**ECS = 4.9 K**




**Yrs 1-150**
**ECS = 5.5 K**




**Yrs 1-200**
**ECS = 6.0 K**




**If non linear relationship,**
**ECS strongly depends on the chosen period**
**=> It is hard to give a number for ECS**

# Outline

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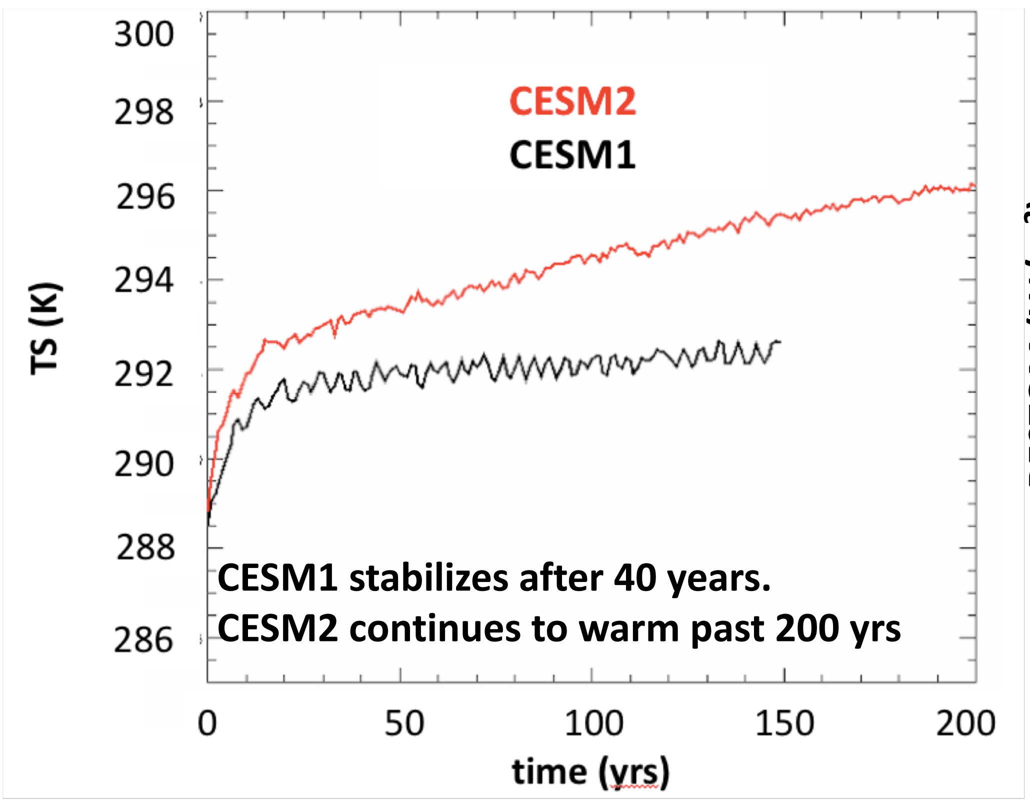
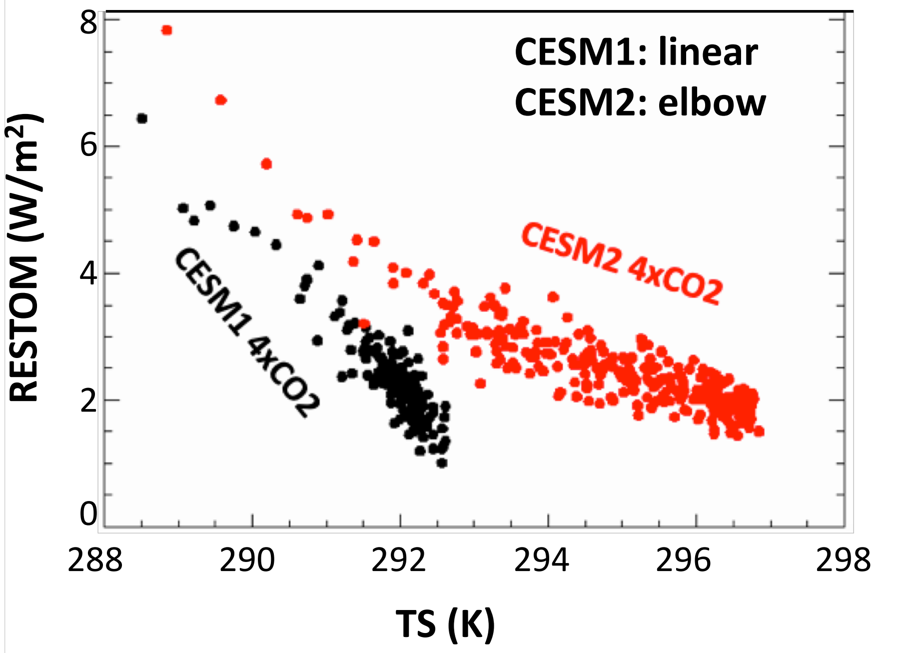
# What can we learn from 4XCO2 runs ?

**We cannot give an exact number for climate sensitivity**
**Nevertheless the 4xCO2 behavior is different in CESM1 and CESM2**

Increase in TS after abrupt 4XCO2




"Gregory Plot" (RESTOM vs TS)




**Can we identify the changes responsible for this ?**

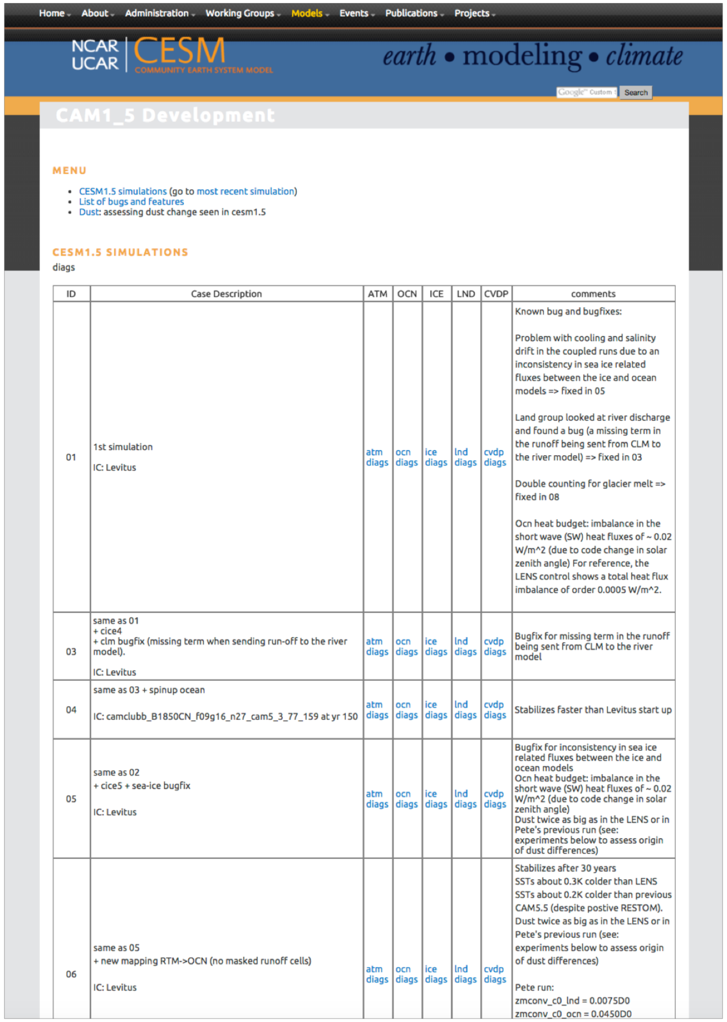
# The long road from CESM1 to CESM2

**First coupled simulation in Nov 2015**

**Release in June 2018**

**297 development configurations**
**CESM2_v1 => first coupled run**
**CESM2_v297 => official CESM2**

**Thousands of simulated years and diagnostics.**



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CAM1_5 Development

MENU

- CESM1.5 simulations (go to most recent simulation)
- List of bugs and features
- Dust: assessing dust change seen in cesm1.5

CESM1.5 SIMULATIONS

diags

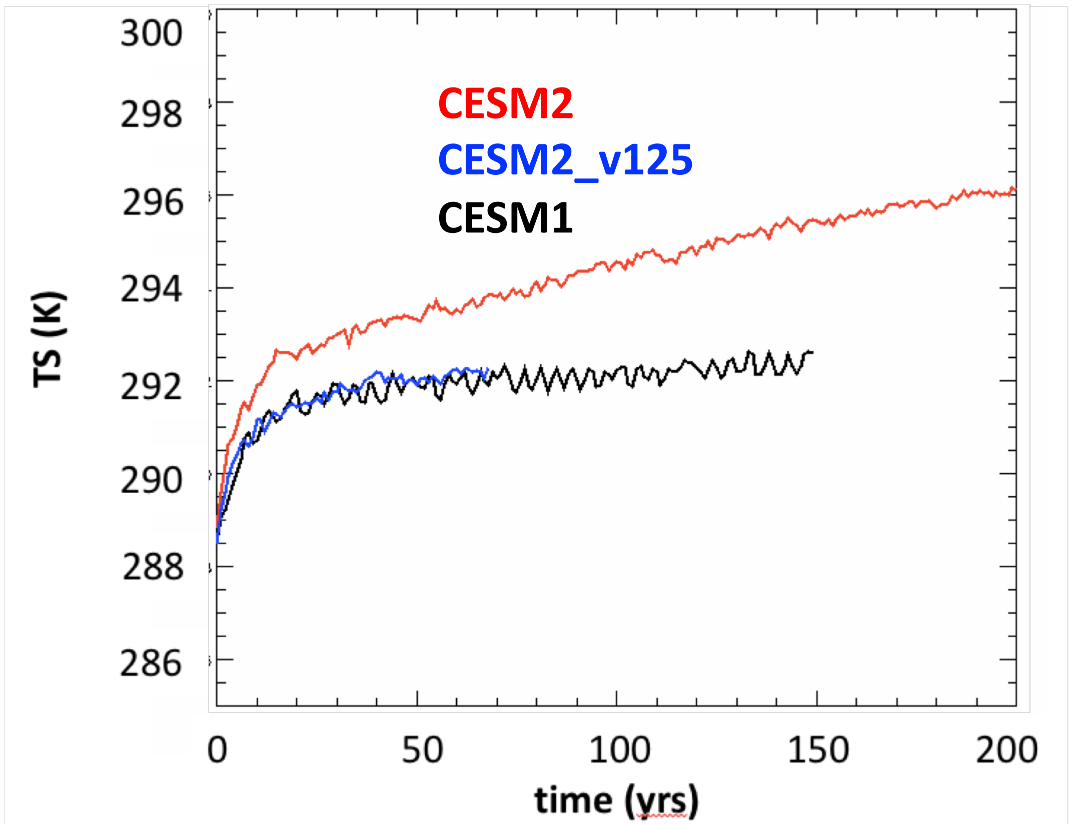
| ID | Case Description | ATM | OCN | ICE | LND | CVDP | comments |
|---|---|---|---|---|---|---|---|
| 01 | 1st simulation<br>IC: Levitus | atm diags | ocn diags | ice diags | lnd diags | cvdp diags | Known bug and bugfixes:<br>Problem with cooling and salinity drift in the coupled runs due to an inconsistency in sea ice related fluxes between the ice and ocean models => fixed in 05<br>Land group looked at river discharge and found a bug (a missing term in the runoff being sent from CLM to the river model) => fixed in 03<br>Double counting for glacier melt => fixed in 08<br>Ocn heat budget: imbalance in the short wave (SW) heat fluxes of ~ 0.02 W/m^2 (due to code change in solar zenith angle) For reference, the LENS control shows a total heat flux imbalance of order 0.0005 W/m^2. |
| 03 | same as 01<br>+ cice4<br>+ clm bugfix (missing term when sending run-off to the river model).<br>IC: Levitus | atm diags | ocn diags | ice diags | lnd diags | cvdp diags | Bugfix for missing term in the runoff being sent from CLM to the river model |
| 04 | same as 03 + spinup ocean<br>IC: camclubb_B1850CN_f09g16_n27_cam5_3_77_159 at yr 150 | atm diags | ocn diags | ice diags | lnd diags | cvdp diags | Stabilizes faster than Levitus start up |
| 05 | same as 02<br>+ cice5 + sea-ice bugfix<br>IC: Levitus | atm diags | ocn diags | ice diags | lnd diags | cvdp diags | Bugfix for inconsistency in sea ice related fluxes between the ice and ocean models<br>Ocn heat budget: imbalance in the short wave (SW) heat fluxes of ~ 0.02 W/m^2 (due to code change in solar zenith angle)<br>Dust twice as big as in the LENS or in Pete's previous run (see: experiments below to assess origin of dust differences) |
| 06 | same as 05<br>+ new mapping RTM->OCN (no masked runoff cells)<br>IC: Levitus | atm diags | ocn diags | ice diags | lnd diags | cvdp diags | Stabilizes after 30 years<br>SSTs about 0.3K colder than LENS<br>SSTs about 0.2K colder than previous CAM5.5 (despite postive RESTOM).<br>Dust twice as big as in the LENS or in Pete's previous run (see: experiments below to assess origin of dust differences)<br>Pete run:<br>zmconv_c0_lnd = 0.0075D0<br>zmconv_c0_ocn = 0.0450D0 |

http://www.cesm.ucar.edu/working_groups/Atmosphere/development/cesm1_5/

**Can we identify the changes responsible for change in climate sensitivity ?**

# Abrupt 4xCO2 in intermediate configurations

Increase in TS after abrupt 4XCO2




**Abrupt 4xCO2 in some intermediate configurations**

**CESM2_v125 similar to CESM1**

**CESM2 ⇔ CESM2_v125**
**Differences in atm, lnd, ocn, sea-ice**

**=> Let's start with the atm**

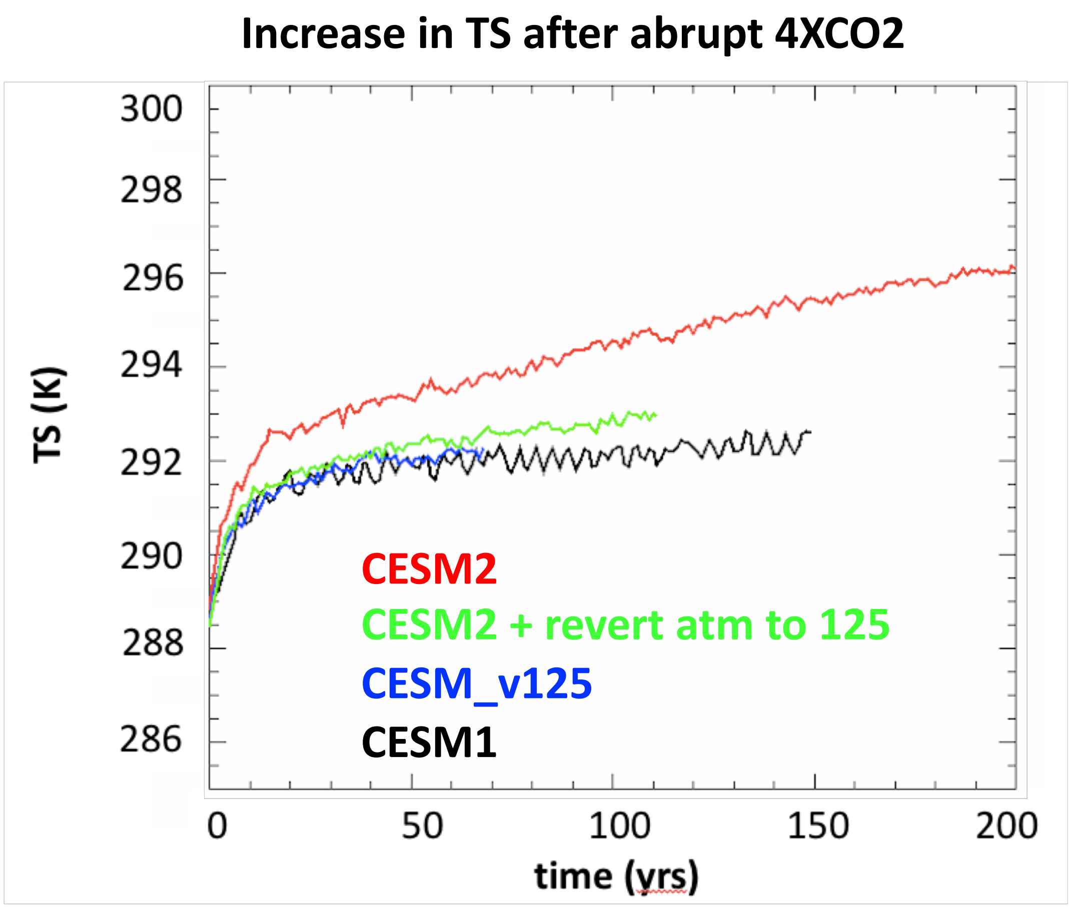
# Revert the atmosphere to CESM2_v125

**Step 1: Identify atm-only mods between CESM2_v125 and CESM2**

- New topography
- Dust tuning
- Cmip6 emissions
- Orbital change
- WACCM forcing 3-mode
- WACCM forcing (ozone, stratospheric aerosol, tracer)
- Bugfix for vertical remapping
- Bugfix for MG2
- Bugfix for water conservation
- Background volcanoes
- New autoconversion (KK)
- Decrease so2 lifetime
- Increase iterations for sfc fluxes
- Mahrt and Sun sfc flux adjustement
- new H2O external forcing
- washout fix for SO2
- fix for O3 above the CAM top,
- Tuning parameters
  - gamma coeff
  - Bergeron Factor
  - zmconv_ke
  - Dcs

**Step 2: Take CESM2 and revert the atmosphere to 125**

# Atmosphere changes explains only part of the story




Reverting the atmosphere to CESM2_v125

$\Rightarrow$ bring us back part way to CESM1 behavior

# Can we narrow down the list ?

## List of mods to revert atm to CESM2_v125

- New topography
- Dust tuning
- Cmip6 emissions
- Orbital change
- WACCM forcing 3-mode
- WACCM forcing (ozone, stratospheric aerosol, tracer)
- Bugfix for vertical remapping
- Bugfix for MG2
- Bugfix for water conservation
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- New autoconversion (KK)
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- washout fix for SO2
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  - Bergeron Factor
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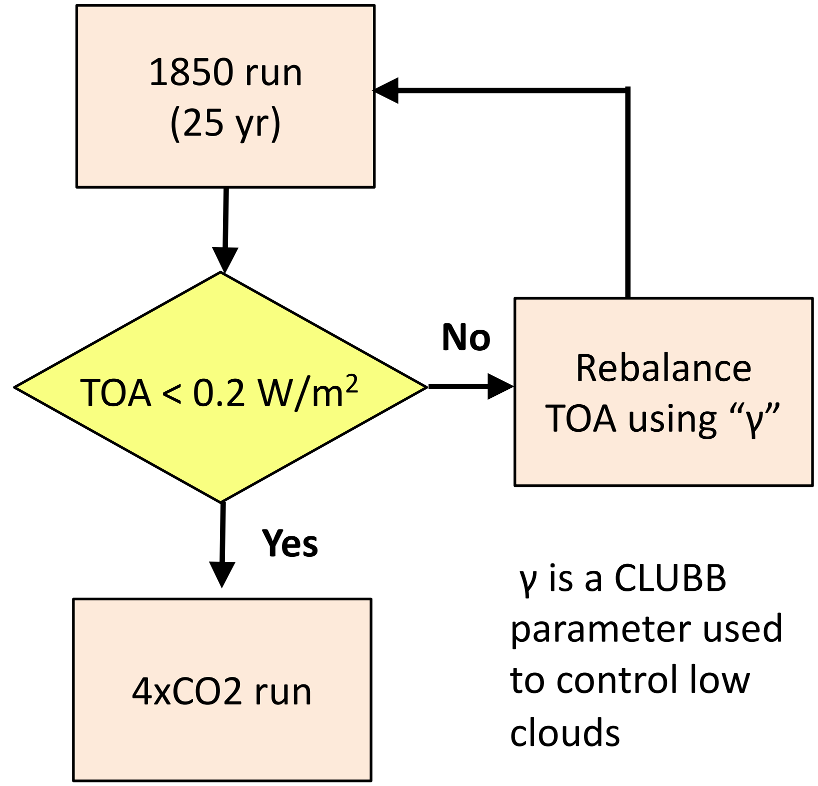
  - Dcs

## Require usual CESM2 tuning cycle



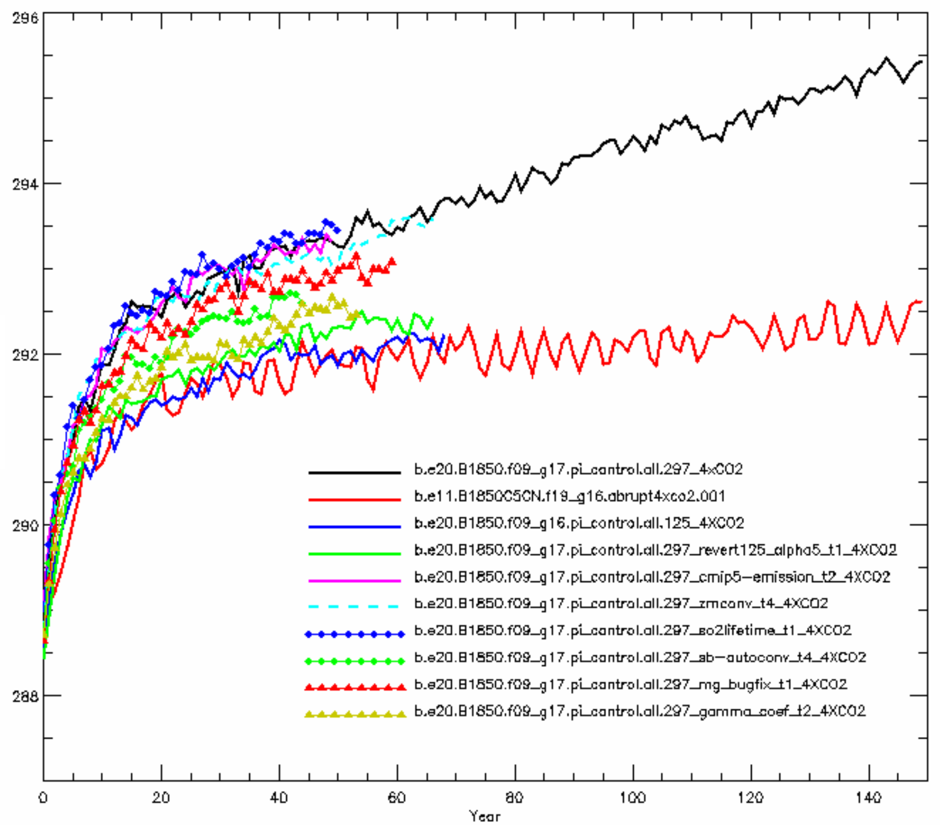

γ is a CLUBB parameter used to control low clouds

Courtesy Julio Bacmeister

# Preliminary results

**Increase in TS after abrupt 4XCO2**

TS (K)




**Time (yrs)**

## What seems to make a difference ?

**Makes a difference**

- Autoconversion (KK/SB)
- MG2 bugfix (+zmconv_ke)
- gamma_coeff

**Makes no difference**

- zmconv_ke
- $SO_2$ lifetime
- CMIP6 emissions

**Caveat**

- gamma_coeff retuning

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# Slab Ocean Model experiments

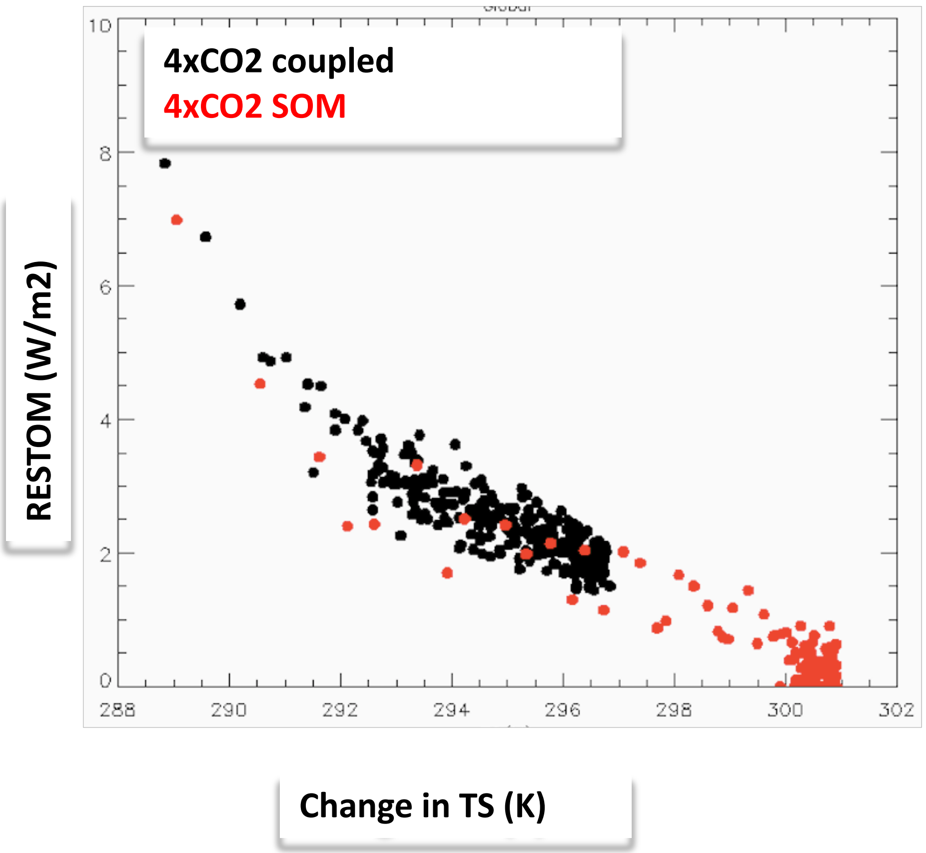
## Slab Ocean Model (SOM)

- Ocean = static layer of water with some heat capacity but no motion.
- Net heat transport by ocean currents is prescribed => "q-flux"
- Reduces the time required for the model to reach equilibrium

## Q-flux

- Derived from 50 years of B1850 (to capture Arctic variability)
- Time invariant but geographically-varying mixed layer depth
- Global mean of q-flux = zero by construction

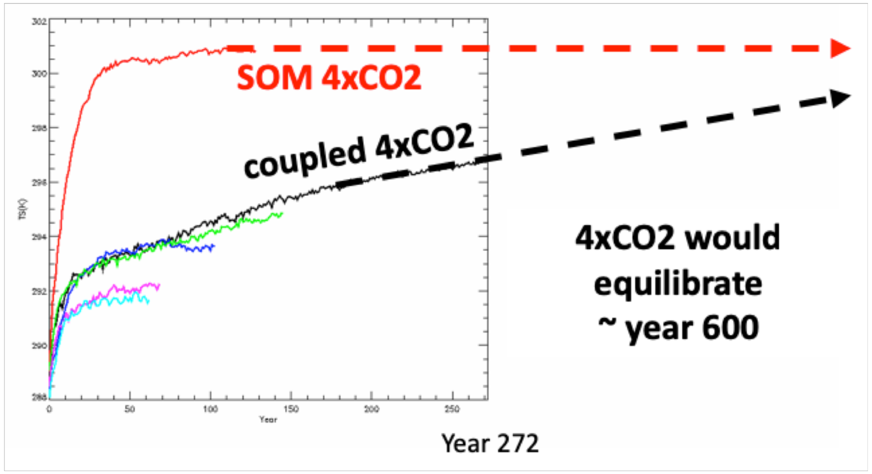
# Gregory Plots for 4x$CO_2$ SOM runs



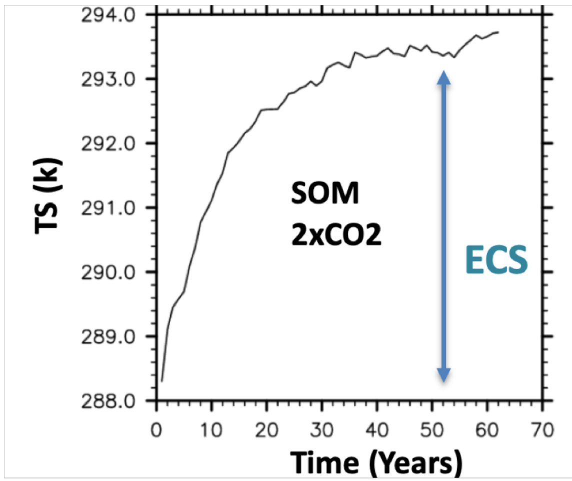

SOM runs reach equilibrium faster

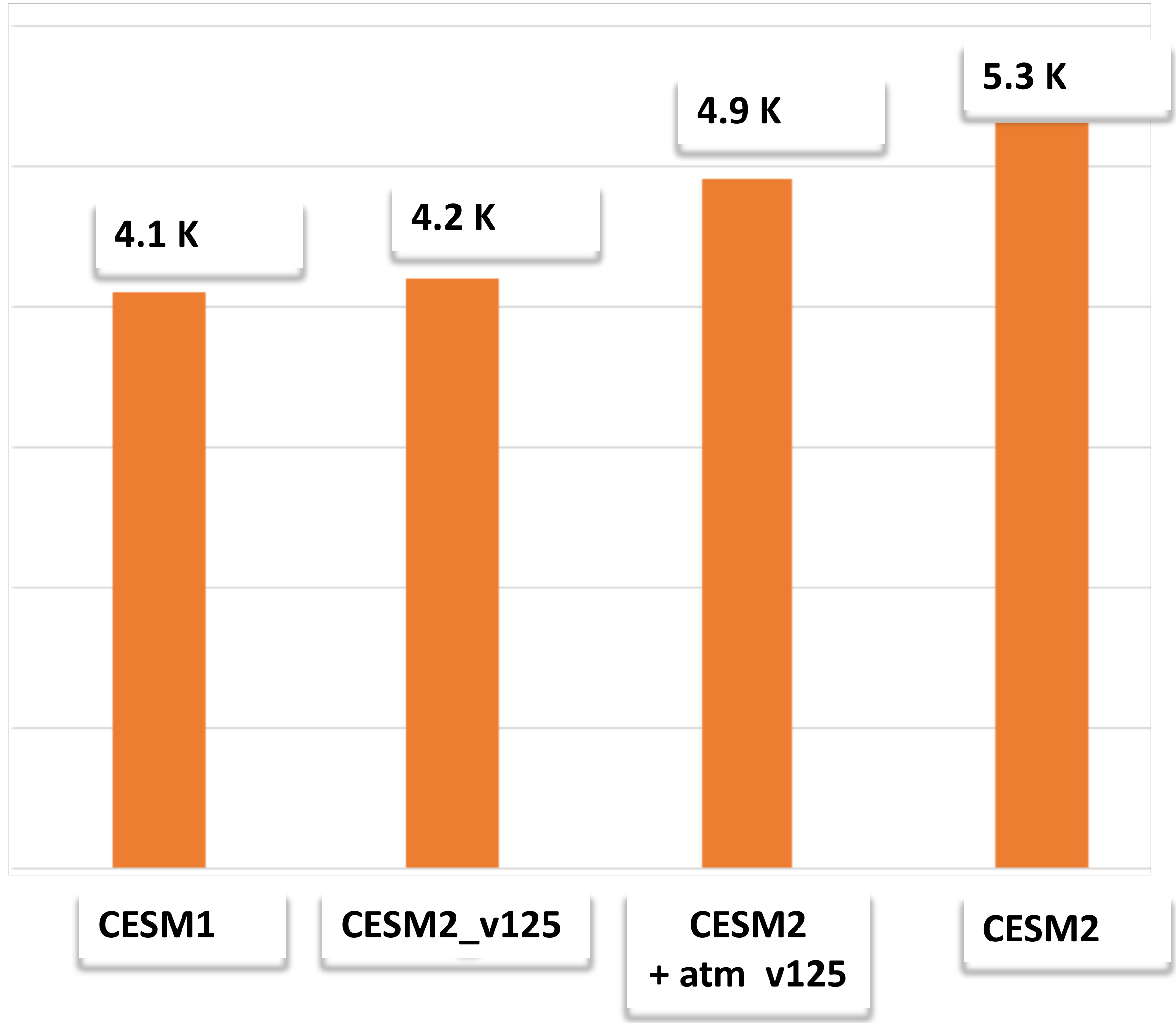
Gregory plot for SOM run is similar to the coupled run

The ocean dynamics has minimal impact ?



# Equilibrium Climate Sensitivity for $2xCO_2$ SOM runs




**Change in the atmosphere are only part of the story**

# Conclusions

- CESM2 has a higher sensitivity
- Abrupt 4xCO2 behavior is different in CESM1 and CESM2
  CESM1 stabilizes after 40 years.
  CESM2 continues to warm past 200 yrs
- Gregory plots for 4xCO2 SOM and 4xCO2 coupled runs are similar
  Only the timescale is different
  Ocean dynamics has minimal impact
- Equilibrium Climate Sensitivity in SOM runs is consistent with 4XCO2 coupled runs
- What is the culprit ?
  Atmosphere is one of the culprits

# What is next ?

- 4xCO2 and SOM runs show atmosphere is only part of the story
  => We are looking at the impact of the other components

- Simple one-box Energy balance Model (EBaM)
  => EBaM can reproduce many features of 4xCO2 coupled runs

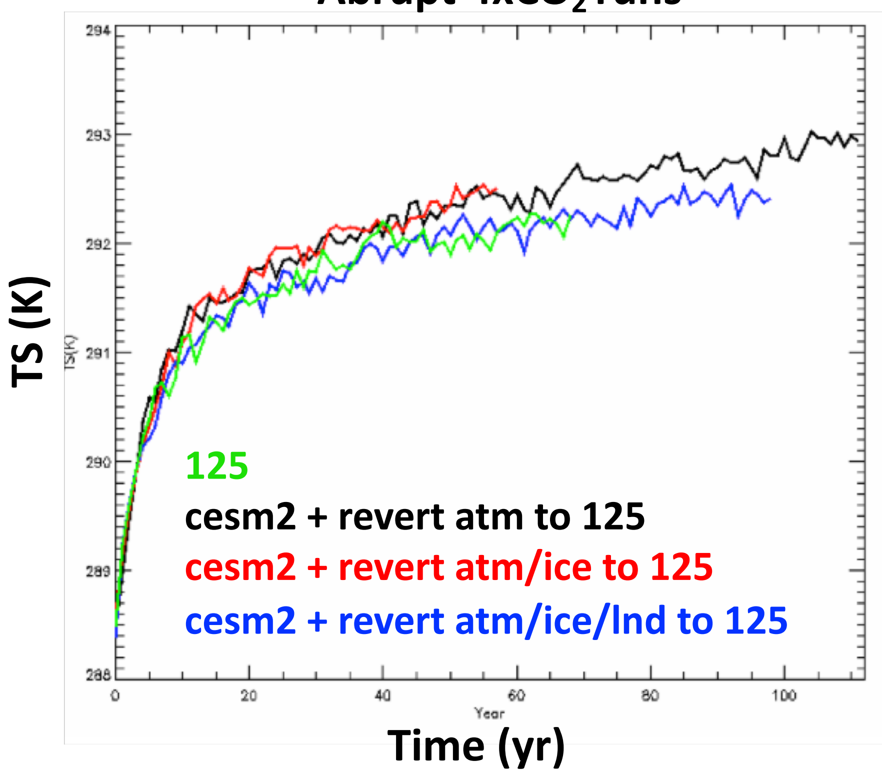
- Idealized SOM experiments
  => Idealized q-fluxes with constant mixed layers

# Impact of the other components

**Between 125 ⬄ CESM2**

- Change in sea-ice albedos
- Change in land parameters (and many other things)
- Change in ocean coupling frequency and Robert filter

**Abrupt 4x$CO_2$ runs**




Reverting atmosphere and land parameters to 125 reverts to CESM1 behavior

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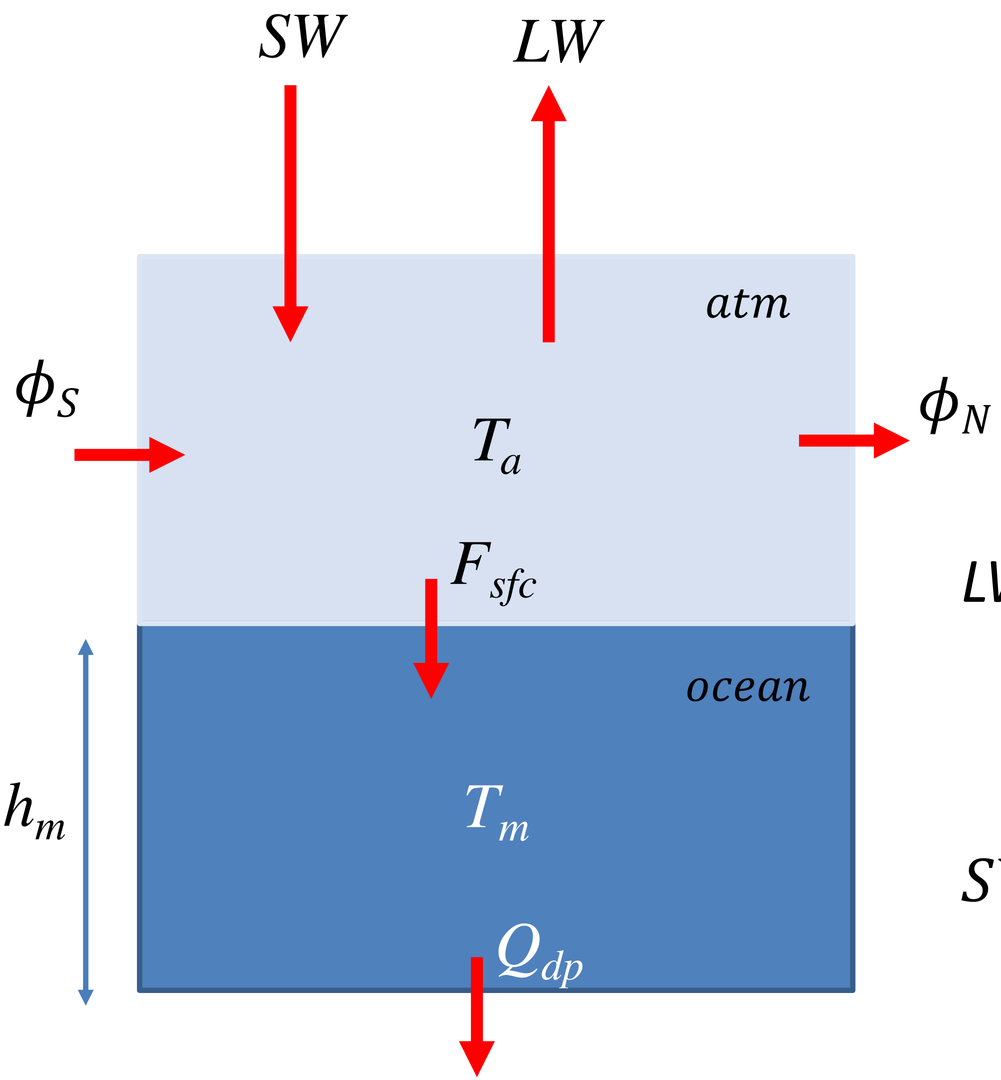
# Simple one-box Energy balance Model (EBaM)




***Approximations***

$$\phi_S = \phi_N = 0$$

*Heat capacity of atm* $\ll$

$$Q_{dp} = constant$$

**Greenhouse effect:** CO2, Water vapor, high clouds

$$LW = \sigma T_{eff}^4 \; ; \; T_{eff} = \lambda(T_m) T_m$$

**SW albedo:** Clouds, snow, ice ....

$$SW = \alpha(T_m) S_0^{\downarrow} ; \;\; S_0^{\downarrow} = \textit{incoming solar}$$

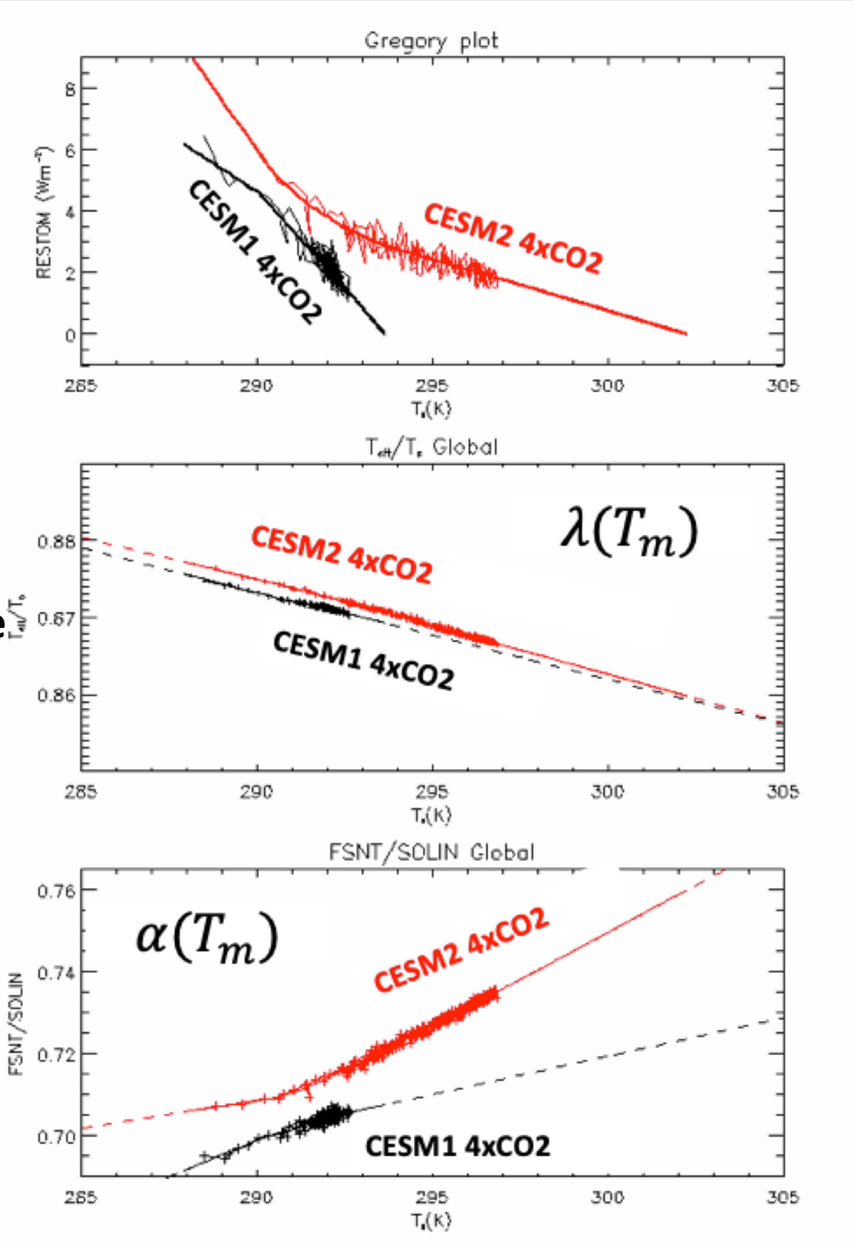
Courtesy: Julio Bacmeister

# Simple one-box Energy balance Model (EBaM)

Gregory plot

LW Greenhouse effect

SW Albedo




***"Elbow" in albedo curve produces nonlinearity in Gregory plot***

***Slope of $\alpha$ determines climate sensitivity***

Courtesy: Julio Bacmeister

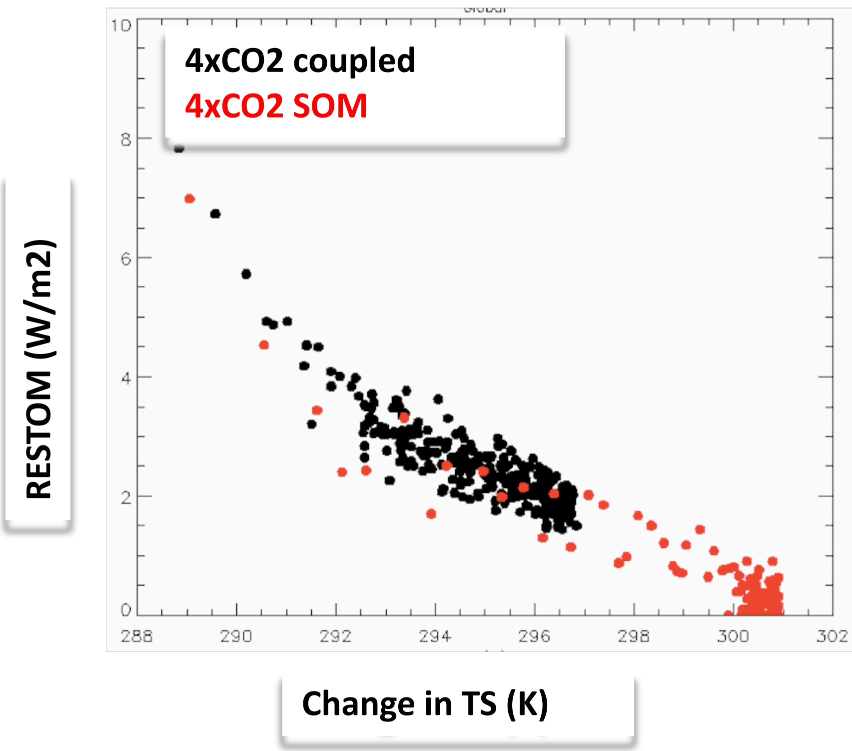
# What is next ?

- 4x$CO_2$ and SOM runs show atmosphere is only part of the story
  => We are looking at the impact of the other components

- Simple one-box Energy balance Model (EBaM)
  => EBaM can reproduce many features of 4x$CO_2$ coupled runs

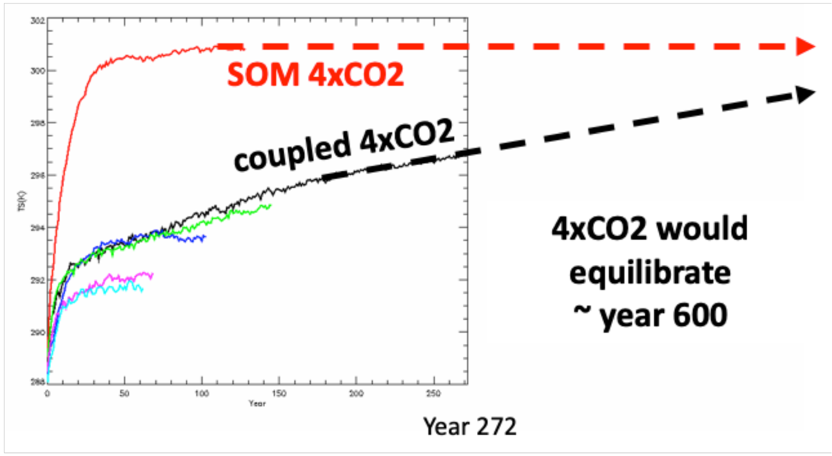
- Idealized SOM experiments
  => Idealized q-fluxes with constant mixed layers

# Reminder:  4x$CO_2$ coupled <=> SOM runs

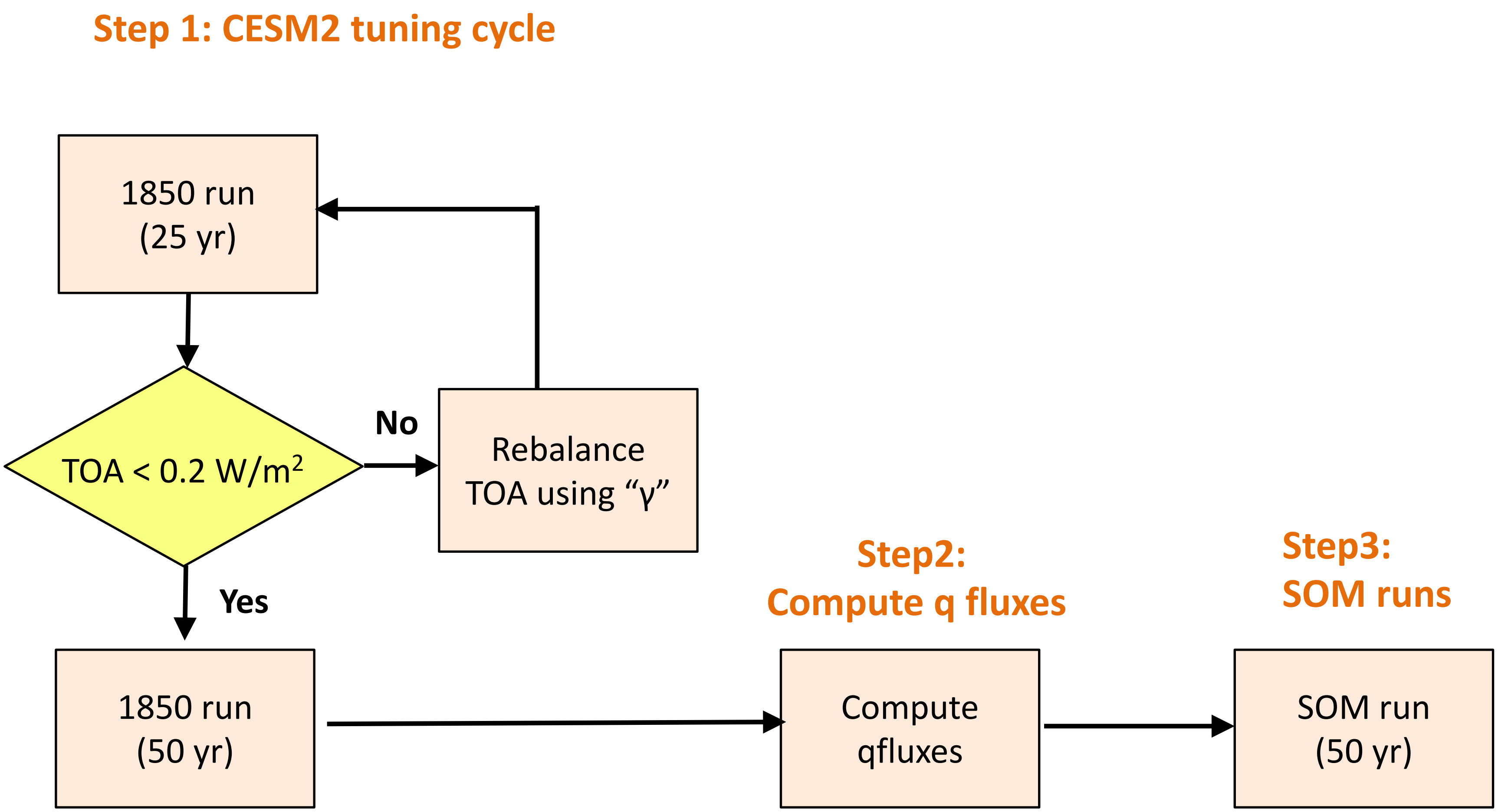



Temperature timeseries and Gregory plots are consistent

SOM is “cheaper”          But still…



# Steps for a SOM run



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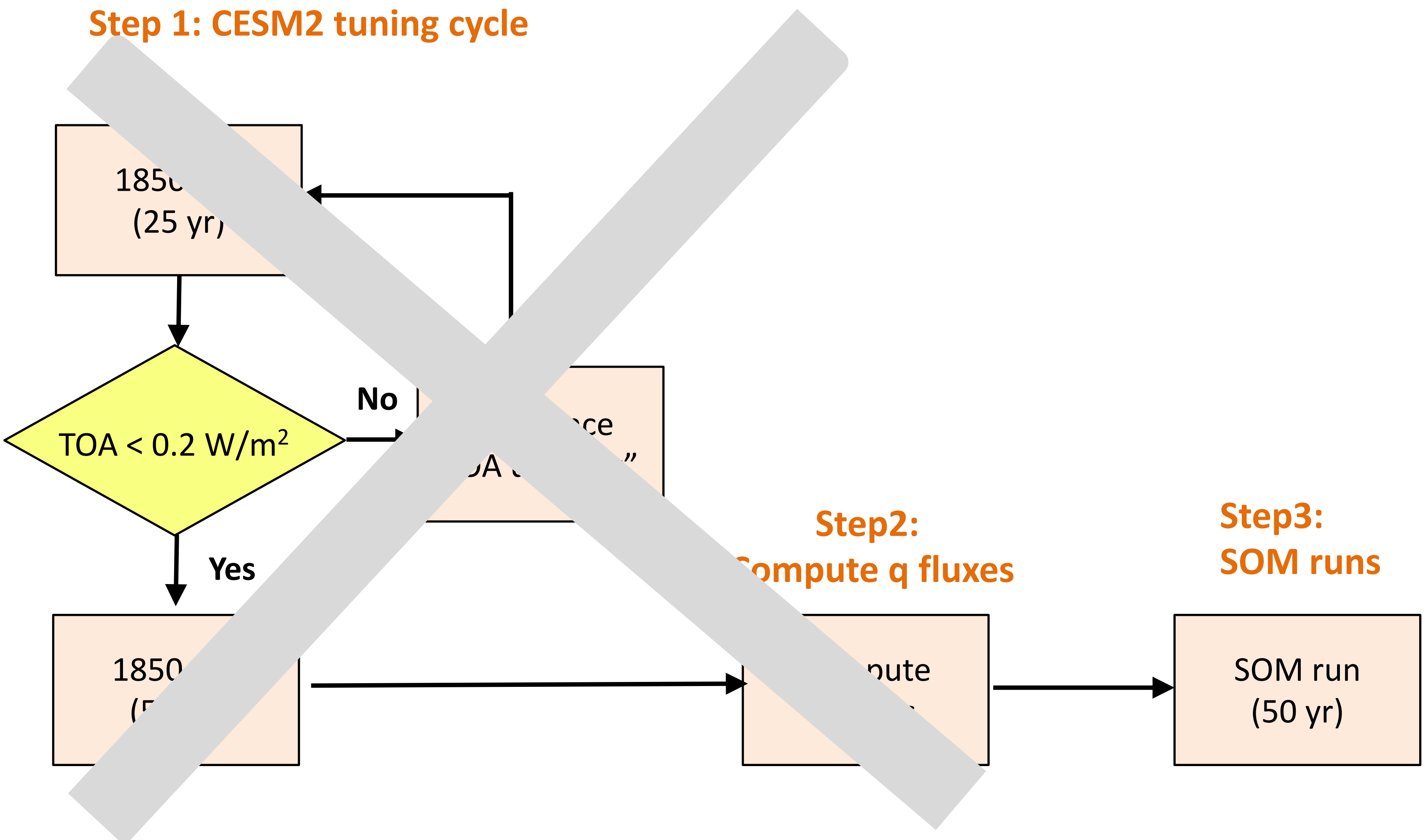


**Idealized q-fluxes with constant mixed layers => Eliminate steps 1 and 2**

# Questions ?